Monetary Values for Air Pollution Risk of Death: A Contingent Valuation Survey

Olivier Chanel, Stephane Luchini

GREQAM

Groupement de Recherche en Economie
Quantitative d'Aix-Marseille - UMR-CNRS 6579
Ecole des Hautes Etudes en Sciences Sociales
Universités d'Aix-Marseille II et III

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Olivier CHANEL
Stéphane LUCHINI

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Olivier Chanel
GREQAM-IDEP
CNRS

Stéphane Luchini
GREQAM-IDEP
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Abstract

In this paper, we extend the individual dynamic model of life-time resource allocation to assess the monetary value given to the increase in survival probabilities of every member of a household induced by improved air quality. We then interpret this monetary value as a flow of Value of Life Years Lost (VOLY), and estimate the corresponding Value of a Prevented Fatality (VPF) for different ages and different household members. Using French contingent valuation data on air pollution, we estimate a mean VOLY of €150,000 and a mean VPF of €2.15 million. In addition, we find an inverse U-shaped relationship between age and VPF.

Keywords: Value of statistical life, Air pollution, Familial Altruism, Contingent Valuation.

JEL Classification: D6, C9

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†Corresponding author: Olivier Chanel. GREQAM, 2 rue de la Charité, F-13002 Marseilles, France, e-mail: `olivier.chanel@univmed.fr`.

1 Introduction

Public economics has always been concerned with the awkward albeit necessary task of valuing life with a view to upgrading economic efficiency in public policies involving changes in death probability. Since no market exists for life, a value for a reduction in probability of death needs to be deduced from stated or revealed economic behaviour. Empirical assessments have so far provided a range of values generally between € 0.7 and € 6.1 million. One important finding has been that the Value for Preventing a statistical Fatality (VPF) depends on the characteristics of the risk of death: age at death, quality of life and nature of the underlying risk have largely been found to be relevant factors (see for instance Slovic, 1987; Cropper et al., 1994; Krupnick et al., 2002, Alberini et al., 2004). As a consequence, "accurate valuation requires the use of scenario-specific values" (Hammitt, 2007). VPF should therefore depend on the specific context of the Cost Benefit Analysis (CBA), and may even vary within the same CBA when the underlying risk of death and the age of the population differ.[1]

However, although numerous studies assess monetary values that can be used in accidental contexts (in transportation, at work, harmful substances in food or medications) very few deal with environmental hazards. For risk of death from air pollution, which has been a growing source of concern in recent years, the practice has been to apply a correction factor: UK DH (1999) proposed 0.7; Sommer et al. (1999) 0.61, Ostro and Chestnut (1998), 0.8 and Pearce and Crowards (1996) 0.7, in the absence of the assessment of specific monetary values (to our knowledge, there are only two for developed countries: Chanel et al., 2004, Chilton et al., 2004).

In this paper, we address this issue and assess a VPF specific to air pollution risk of death. We do so by implementing a CV survey that collects Willingness To Pay (WTP) for a change in air pollution exposure. The hypothetical scenario, derived from Viscusi et al. (1988) and Guria et al. (1999), proposes a hypothetical choice between moving with his/her household to one of two cities, which are exactly the same (city size, housing, weather, public services etc.) with the exception of the cost of living and the level of air pollution. By privatizing the public commodity air pollution, we succeed in ruling out any form of altruism (towards other persons

[1] An intuitive example is the construction of a new highway in the middle of the countryside. The decision-maker should value differently deaths avoided thanks to this safer road infrastructure and deaths attributed to greater exposure of residents to air pollution.

today and towards future generations) except altruism towards one's family. The survival of every member of the household is then considered as a household public good (Bergstrom, 1997).

To analyze the data and compute a VPF specific to air pollution, we adapt a lifetime resource allocation model to the whole household, taking into account the expected remaining lifetime of each member. This model allows us to disentangle the potential benevolence of respondents towards other household members and to compute an individual VPF based on a weighted sum of the discounted value of a life year. Our results are three-fold. First, we show that only children under eighteen are taken into account for by respondents when they state their preferences for moving to a less polluted city, with no concern for other adults of the household. Second, the mean value of a life year equals € 150,000 with a discount rate of 6.4%. Third, the econometric estimations lead to an inverse U-shaped relationship between VPF and age with a maximum of € 2.5 million at age 41.

The remainder of the paper proceeds as follows. Section 2 presents the theoretical model and Section 3 the survey design and data. In section 4, we define a structural econometric model based on the theoretical framework. The econometric results are given in Section 5. We conclude in Section 6.

2 Theoretical framework

Consider a household composed of $\bar{n}$ individuals indexed by n, $n = 1, ..., \bar{n}$ of age j^n, with an upper bound T on the age to which they can survive. Each household has a utility function at age t denoted $u_t(.)$, strictly concave, twice continuously differentiable, additive and time-separable.

Define the mortality rate of a j-year-old individual as μ_j. The probability of becoming at least t-year-old is denoted S_t, and depends on the successive mortality rates as follows:[2]

$$S_t = e^{-\int_0^t \mu(s)ds} \tag{1}$$

[2]Blanchard (1985) showed that age-dependent death rates could result in time inconsistency. We however neglect this issue, as most authors do.

The probability of being alive at age t conditional on having survived until age j is a survivor function denoted by $S_t/S_j = S_{t,j}$. Assume that one of the household members (by convention, indexed by $n = 1$ in the following) maximizes the sum of the expected remaining lifetime utility of each household member conditional on his/her survival at age j^n:[3]

$$\max_{c_{j^n+t}} E\left[u(c_{j^n})\right] = \int_0^{T-j^1} e^{-\delta_t t} \sum_{n=1}^{\bar{n}} S_{j^n+t,j^n} u(c_{j^n+t}) dt \tag{2}$$

where $E[.]$ denotes an expectation operator; $u(.)$ is assumed to be increasing in c; T denotes the maximum age an individual can reach; c_{j^n+t} denotes consumption at age $j^n + t$; and δ_{j^1+t} denotes the marginal rate of time preference, possibly time-dependent.[4]

In the usual model of lifetime resource allocation with a complete set of life annuities, each individual is supposed to choose an intertemporal consumption profile that depends on his/her current accumulated assets, his/her expected future incomes y_t, $t = j, \ldots, T$, and the opportunities to borrow and invest on capital markets.

This requires the existence of a complete and perfect market for life annuities allowing the consumption of those who survive to be financed by the assets of those who die. In such a world, individuals would choose consumption profiles satisfying an expected lifetime budget constraint. Despite the fact that such a world does not exist, Blomqvist (2002) noticed that the family often operates monetary transfers towards its oldest members and that advanced countries offer private annuities markets and publicly funded pension schemes that guarantee a minimum consumption level for everyone. Hence, we assume that the household's perceived expected lifetime budget constraint is:

$$\int_0^{T-j^1} e^{-rt} \sum_{n=1}^{\bar{n}} S_{j^n+t,j^n} (y_{j^n+t} - c_{j^n+t}) dt = 0 \tag{3}$$

where y_{j^n+t} denotes individual incomes at age j^n+t, $t \geqslant 0$, and r is a constant market rate of interest.

Maximization of (2) subject to (3) provides the optimal consumption profile $c^*_{j^n+t}$ of the individual on remaining expected lifetime (Blomqvist, 2002). The conditions

[3] This model extends the model proposed in Chanel et al. (2004) by explicitly taking into account all household members and introducing the VOLY.

[4] Note however that a varying discount factor can lead to time inconsistency in life-cycle models (see Blanchard, 1985; or Johansson, 2002).

for optimality, and continuous differentiability of c_{j^n+t}, can be found in Seierstad and Sydsaeter (1987) for an n-year-old individual model. However, to our knowledge, there is no framework for heterogeneous individuals of a household in continuous time, although related dynamic optimization models for heterogeneous agents have been explored in discrete time (see for instance Le Van, Nguyen and Vailakis, 2007).[5] Since we do not need to characterize the optimal consumption profile $c^*_{j^n+t}$ and the λ^* (as shown below), we use the following Hamiltonian:

$$H_t = \int_0^{T-j^1} e^{-\delta_t t} \sum_{n=1}^{\bar{n}} S_{j^n+t,j^n} u(c_{j^n+t}) dt + \lambda^* \int_0^{T-j^1} e^{-rt} \sum_{n=1}^{\bar{n}} S_{j^n+t,j^n} (y_{j^n+t} - c_{j^n+t}) dt \tag{4}$$

where λ is a Lagrange multiplier and the subscript '*' denotes optimal values. It is hence possible to define the monetary counterpart of the expected remaining present value utility $V_{j^1}/\lambda^*(j^1)$ (Johansson, 2001; and Blomqvist, 2002):

$$\frac{V_{j^1}}{\lambda^*(j^1)} = \frac{1}{\lambda^*(j^1)} \int_0^{T-j^1} \left\{ \sum_{n=1}^{\bar{n}} S_{j^n+t,j^n} \left[e^{-\delta_t t} u(c^*_{j^n+t}) \right] + \lambda^* e^{-rt} (y_{j^n+t} - c^*_{j^n+t}) \right\} dt \tag{5}$$

$\lambda^*(j^1)$ should be interpreted as a function standing for the expected present value of the marginal utility of income at age j^1.

Let us now consider a project that induces a change in all the mortality rates at age j^n, μ_{j^n}, and that will last D years. We assume that this change is age-independent and denote it by $d\mu$. This implies a change dS_{j^n+t,j^n} in the conditional survivor function of individuals at age $j^n + t$, $t \geqslant 0$. Let WTP be the willingness to pay of the household for this project and hence for dS_{j^n+t,j^n}. It is then possible to determine the WTP that would leave expected utility unchanged, i.e.:

$$\int_0^{T-j^1} \left\{ \sum_{n=1}^{\bar{n}} dS_{j^n+t,j^n} \left[e^{-\delta_{j^1+t} t} u(c^*_{j^n+t}) \right] + \lambda^* e^{-rt} (y_{j^n+t} - c^*_{j^n+t}) \right\} dt - \lambda^*(j^1) WTP = 0 \tag{6}$$

and $V_{j^1}/\lambda^*(j^1)$ is defined by (5) and (6) as:

$$\frac{V_{j^1}}{\lambda^*(j^1)} = \frac{WTP \int_0^{T-j^1} \left\{ \sum_{n=1}^{\bar{n}} S_{j^n+t,j^n} \left[e^{-\delta_t t} u(c^*_{j^n+t}) \right] + \lambda^* e^{-rt} (y_{j^n+t} - c^*_{j^n+t}) \right\} dt}{\int_0^{T-j^1} \left\{ \sum_{n=1}^{\bar{n}} dS_{j^n+t,j^n} \left[e^{-\delta_t t} u(c^*_{j^n+t}) \right] + \lambda^* e^{-rt} (y_{j^n+t} - c^*_{j^n+t}) \right\} dt} \tag{7}$$

[5] The introduction of several individuals affects the optimization setting in a linear way. The proofs of existence and unicity of the solution remain valid, although the values of the solutions obviously differ.

Let us consider that the project changes the mortality rate during a short time interval D (a blip according to the terminology of Johanesson et al., 1997). Let S_{j^n+t,j^n} ($\tilde{S}_{j^n+t,j^n},$) be the survivor function of member n at age j^n before (after) the project is implemented, before (after) the change $d\mu$ in the mortality rate. We have:

$$\tilde{S}_{j^n+t,j^n} = e^{-\int_{j^n}^{j^n+D}[\mu(s)-d\mu]ds} e^{-\int_{j^n+D}^{t}\mu(s)ds} = e^{Dd\mu} S_{j^n+t,j^n} \qquad n = 1, ..., \bar{n} \tag{8}$$

Hence, we have the following for small $Dd\mu$:

$$dS_{j^n+t,j^n} = \tilde{S}_{j^n+t,j^n} - S_{j^n+t,j^n} = S_{j^n+t,j^n}\left(e^{Dd\mu} - 1\right) \approx S_{j^n+t,j^n} Dd\mu \tag{9}$$

and then (7)simplifies to:

$$\frac{V_{j^1}}{\lambda^*(j^1)} = (Dd\mu)^{-1} WTP \tag{10}$$

Expression (10) constitutes a very simple way to compute the monetary counterpart for a household with $\bar{n}$ j^n-year-old individuals, $n = 1, ..., \bar{n}$ only based on the WTP for a (age-independent) contemporaneous variation $d\mu$ of the mortality rate of each of its members.

In the case of a single j-year-old individual, Equation (10) is interpreted as the Value of Preventing a Fatality (VPF) at age j (see Johansson, 2001 or Blomqvist, 2002). In the present framework, as the WTP stands for all the members of a household, the monetary counterpart to the expected remaining present value utility $V_{j^1}/\lambda^*(j^1)$ can no longer be interpreted in terms of one single VPF.[6] One can thus assume that it corresponds to the sum of the VPFs of each member of the household:

$$\frac{V_{j^1}}{\lambda^*(j^1)} = \sum_{n=1}^{\bar{n}} VPF_n \tag{11}$$

Each of these VPFs can itself be expressed as a flow of discounted age-independent Value Of Lost Years (VOLY) as Viscusi et al. (1997) or Hurley et al. (2005) did in a discrete-time framework or Leksell and Rabl (2001) in a continuous-time framework.[7]

[6]Note that the WTP could be corrected to establish a VPF per member by dividing the WTP by the number of members in the household, and then computing a VPF per member. Studies applying hedonic methods for computing VPF generally proceed in this way without specific weighting, whereas empirical macroeconomics studies sometimes use different weights according to the age of the different members.

[7]Economists have long known that people discount future outcomes, and "future years should be no exception" (Viscusi et al., 1997).

Hence, the VPF for a j-year-old individual may be expressed as:

$$VPF_j = \int_j^T e^{-\delta(t-j)} S_{t,j} VOLY dt \tag{12}$$

Combining equations (11) and (12) gives:

$$\frac{V_{j^1}}{\lambda^*(j^1)} = (Dd\mu)^{-1} WTP = VOLY \sum_{n=1}^{\bar{n}} \int_{j^n}^{\bar{T}^n} e^{-\delta(t^n - j^n)} S_{t^n,j^n} dt^n \tag{13}$$

where $\bar{T}^n$ represents the age up to which the member n of the household is supposed to live in the household and δ represents the rate at which future life years are discounted. Note that, for tractability in the empirical study, we assume in equation (13) that all years in a lifetime are equally valued (i) by individuals (in particular, low quality years at advanced ages) and (i') across individuals; (ii) the rate that discounts future years is constant; and (iii) the respondent does not weight his/her household's members other than through their respective age.

3 Survey design and data

The data used in this paper are derived from a stated-preferences experiment designed to explore theoretical and empirical issues related to the risks of air pollution exposure. Respondents were from the Bouches-du-Rhône district (1.8 million inhabitants), which includes Marseilles, the second largest city in France. In the survey, respondents were asked about their WTP to increase the air quality. The first part of the survey required respondents to provide details of their socioeconomic background, risk attitudes, beliefs and knowledge about air pollution and state of health. In the second part, the scenario was described and WTP was elicited.

The scenario, derived from Viscusi et al. (1988) and Guria et al. (1999), proposed a hypothetical choice between moving with his/her household to one of two cities which are exactly the same (city size, housing, weather, public services etc.) with the exception of the cost of living and the level of air pollution.[8] By moving to a less polluted place, the respondent was offered the opportunity to improve air quality for him/herself and other members of his/her household (see Appendix B

[8] Air quality in Marseilles, the largest city of the district, was used as a reference point for all respondents.

for the hypothetical scenario). Our scenario therefore focuses on a private action – choosing which city your household will live in – not a public action. This eliminates the potential confounding factors of altruism outside the family. Consequently, the respondent values an improvement in air quality for him/herself and other household members only.[9]

An important issue is how to present mortality risks. In general, people have difficulties handling risk levels, especially small changes in risk (see Pidgeon and Beattie, 1997, Fischhoff, 1989, Hammitt and Graham 1999). In the case of air quality effects on health, the difficulty is to limit this cognitive weakness but to respect epidemiological reality. In the scenario, we chose to express risk changes over a period longer than one year and for a large population (one hundred persons), since natural frequencies are much easier to handle than objective probabilities (Hoffrage *et al.*, 2000; Manski, 2004). The exact wording was: *One person out of 100 randomly chosen in the street is likely to die before 80 due to poor health related to air pollution exposure. This person will have lost around 10 years of life.* This wording is in line with epidemiological data ('will have lost around 10 years of life', 'before 80') and introduces the uncertainty dimension both by mentioning 'randomly chosen in the street' and 'will die before 80' (see Künzli *et al.*, 2000).

We collected WTP data using two methods.[10] First, we used an innovative survey

[9]This scenario also has numerous other methodological advantages. First, it decreases the possibility of strategic behavior: the air quality in both cities will not be changed by individual decisions and future behavior. This thus eliminates strategic biases since it becomes too difficult for a respondent to speculate about the way s/he could manipulate the final decision by formulating a strategic answer. Second, any biases linked to uncertainty about the existence of the good are minimized because no public action is required. Third, familiarity with the hypothetical market is good since the proposed choice set is very close to those respondents are used to dealing with in 'real' life. Personal and economic dimensions dominate in making decisions to move, and this kind of choice is more related to the market sphere than in scenarios that ask for financial contributions to publicly financed environmental improvements. Moreover, even though other criteria are relevant in real decisions to move, the scenario makes apparent the trade-off between two criteria only (air quality and cost of living) by constraining the choice set to two cities similar in their other characteristics. This allows for a better understanding of the exact boundaries of the environmental change, and may reduce embedding effects. Finally, the payment is presented as an addition to current monthly expenditure, reducing the risk of protest responses induced by other payment vehicles such as taxes. Moreover, this monthly payment is *a priori* more closely related to the respondents' reasoning framework: rent, bank loans, water, electricity and phone bills are generally paid every month.

[10]Semi-directive face-to-face qualitative interviews (73 persons) provided information to pre-test

(267 persons) self-administered by following instructions given by the research team. Two sessions of 142 and 125 respondents were organized in the Regional Council conference room, lasting for one hour. WTP revelation questions were computer-assisted with electronic vote sessions (see Chanel *et al.*, 2006). Second, we ran a telephone survey on 1006 respondents by an opinion poll company during July 2000 and July 2001 via computer-assisted telephone interviews using four stratification variables (age, gender, residence and profession). Our sample was representative of the Bouches-du-Rhône population. For each method, WTP questions were asked separately on different aspects of air pollution (mortality effects, morbidity effects and other environmental aspects). In this article, we focus on WTP for a decrease of mortality risks only.

For the initial 1273 interviews, the WTP for a mortality reduction was elicited from 731 out of the 1006 respondents of the telephone survey and all the respondents of the group survey (267). The exploitable sub-sample is 923 respondents. Of these 923 respondents, 4 exhibited unusable responses and 12 exhibited protest responses.[11] This left 907 respondents (see Appendix C for descriptive statistics of the final sample), for whom the survey questions allowed us to identify household: whether the individual is single or lives with other adults and children and their respective age.[12] Finally, the age of each household member allowed us to compute his/her life expectancy according to French epidemiological survival data (Insee, 1999).

4 Econometrics

In this section, we adapt the theoretical model presented in Section 2 to the data. Before proceeding, we first need to specify in the econometric model the variation in mortality risk ($d\mu$) as well as its duration (D).

and refine the survey.

[11]Protest responses are respondents who express nil WTP and give a reason in open comments that can be described as protests (for instance, "I do not agree with the principle of paying", "I would not pay since I will only move to live in the country", "I do not agree to pay to move to a less polluted place when I can die tomorrow when crossing the street" or "I do not want to pay because the factories are the major polluters").

[12]We were unable to identify the structure of the household for six respondents and thus excluded them from the data.

Risk changes are expressed in the scenario over a period greater than one year to avoid too small probabilities. We offer the individual the opportunity to reduce mortality risk by moving to a less polluted place. Three different changes in air pollution levels are used: 25%, 50% and complete elimination (each respondent was assigned randomly to a risk level). We therefore have to compute the annual change $d\mu$ in the death probability corresponding to the scenario, with a parametric function for the conditional survivor function $S_{t,j}$ (see Appendix A). For a 25% reduction of the number of polluted days, $d\mu^4$=0.00022, for a 50% reduction, $d\mu^8$=0.0004328, and for complete elimination , $d\mu^{16}$=0.0008378. The scenario asks each respondent i for a monthly payment WTP_i to reduce the annual death probabilities of his/her household's members by $d\mu_i$. Neglecting infra-annual discounting, monthly WTP is then multiplied by 12 to obtain the annual WTP.[13] The left hand side of Equation (13) simplifies to $(d\mu_i)^{-1}WTP_i$ and can now be computed for each household/respondent.

It now remains to express the right hand side of Equation (13) in a way compatible with the estimation of δ and $VOLY$. Unfortunately, an analytical formulation of the integral in Equation (13) does not exist since S_{t^n,j^n} is itself an integral (see Equation (18) in appendix A). We approximate this expression as follows:[14]

$$(d\mu)^{-1}WTP = VOLY \sum_{n=1}^{\bar{n}} \int_0^{LL_{j^n}} e^{-\delta t^n} dt^n \tag{14}$$

where LL_{j^n} corresponds to life expectancy at age j^n (i.e. $\int_{j^n}^{\bar{T}^n} S_{t^n,j^n} dt^n$). Solving the integral in (14) leads to:

$$(d\mu)^{-1}WTP = VOLY \sum_{n=1}^{\bar{n}} (\delta)^{-1}(1 - e^{-\delta LL_{j^n}}) \tag{15}$$

Adding an error term to the right hand side of this equation makes it a tractable non-linear econometric model. In this formulation, VOLYs are equally weighted for each household member (assumption *iii*), whether the corresponding household member is the respondent him/herself, another adult or a child. This is however a restrictive assumption that can be relaxed and tested for. We do so in the following

[13]As $d\mu$ is lower than 10^{-3} (see above), choosing the duration $D = 1$ makes the approximation error in Equation (9) lower than 10^{-6}.

[14]The trade-off was between using of more tractable survival functions (see for instance the one used in Boucekkine et al.; 2002) that relatively poorly fit observed death rates or keeping the Gompertz function that fits them well but requires the proposed approximation.

non-linear econometric model (hereafter referred to as **Model I**):

$$
\begin{aligned}
(d\mu_i)^{-1}WTP_i = VOLY \big[& \delta^{-1}(1 - e^{-\delta LL_{j^i}}) \\
& + \alpha_a \sum_{a \in Adults} \delta^{-1}(1 - e^{-\delta LL_{j^a}}) \\
& + \alpha_k \sum_{k \in Children} \delta^{-1}(1 - e^{-\delta LL_{j^k}}) + \epsilon_i
\end{aligned} \tag{16}
$$

where $VOLY$ and δ are constant parameters to be estimated; ϵ_i is a well-behaved error term. The parameters α_a and α_k are weights attributed respectively to adult and child-under-18 household members. When $\alpha_k = \alpha_a = 1$, the respondent weights equally all household members and model (16) is therefore in line with the theoretical prediction. When $\alpha_k = \alpha_a = 0$, the respondent only considers his/her own utility gains when stating his/her WTP in the valuation exercise. Based on **Model I**, it is possible to consider that the VOLY depends on a respondent's characteristics such that $VOLY_i = X_i\beta$ where X_i is a set of individual characteristics that capture heterogeneity in VOLY across the sample and β is a vector of parameters (hereafter, referred to as **Model II**). We present empirical results based on these two econometric strategies in the next section.

5 Econometric results

Table 1 presents econometric estimations of **Models I** and **II**. The constant parameter associated with the VOLY in **Model I** is significant and equals 160,700. The second column, devoted to **Model II** estimations, however shows that assuming a respondent-independent VOLY is disputable, since several explanatory variables significantly explain a respondent's VOLY. First, income is significant and positive (*HHIncome*): the VOLY increases with household income. Second, current state of health (*CurHealth*) and expected state of health at age 75 are significant (*Health75*). The former has a negative impact on VOLY (healthier respondents afford less value to future length-of-life gains) while the latter has a positive impact (respondents who expect to be in better health when length-of-life gains occur state a higher VOLY). Declaring regular consumption of organic food (*OrgFood*) increases the likelihood of a higher VOLY. Finally, interviewing the respondent in the Regional Council (*RCinter*) leads to a lower VOLY.

Variable	Model I Parameter estimate	Model I p-value	Model II Parameter estimate	Model II p-value
VOLY estimates				
Constant	1.607e+05	0.005***	1.029e+05	0.033**
Sex	-		-1.667e+04	0.303
Edu2	-		2.893e+03	0.887
Edu3	-		1.239e+04	0.514
BadQuali	-		2.046e+04	0.325
HealthImp	-		1.412e+04	0.405
RCinter	-		-9.210e+04	0.008***
FreshAir	-		3.382e+04	0.118
Hab	-		3.120e+04	0.112
AirPur	-		-5.914e+03	0.920
OrgFood	-		1.381e+04	0.076*
Sport	-		-1.047e+04	0.176
CurHealth	-		-1.000e+04	0.048**
Health75	-		9.743e+03	0.018**
HHIncome	-		4.955e+00	0.004***
Weight for child(ren)				
α_k	1.1999e-01	0.033**	1.105e-01	0.02217**
Weight for other adult member(s)				
α_a	-9.670e-03	0.854	-6.745e-02	0.14748
Discount rate				
δ	9.129e-02	<.001***	6.396e-02	0.00876***
Mean Voly	160700 €		150497.7 €	
Median Voly	-		147994.9 €	

** if p-value<0.05, * if p-value<0.1

Table 1: Non-linear Least Squares Estimation ($N = 907$)

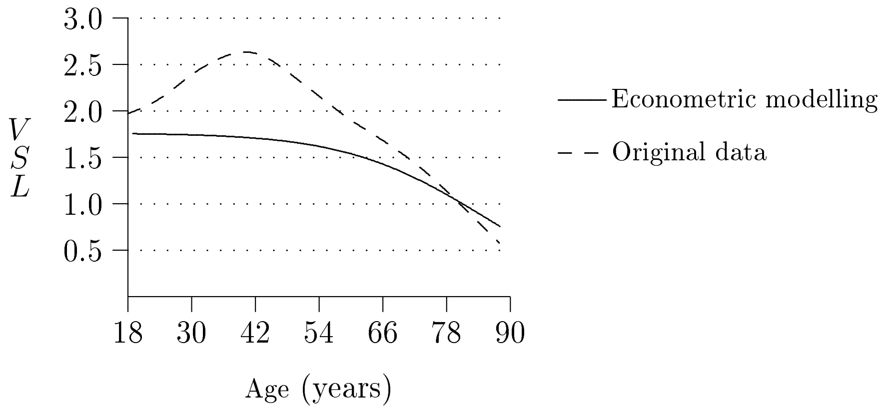
The estimated discount rate for the data equals 9.13% in **Model I** and 6.39% in **Model II**. These results are in line with those reviewed by Frederick, Loewenstein and O'Donoghue (2002). In particular, they report six empirical studies estimating annual discount rates for life years, with corresponding values in the range 0%-3% (Johannesson and Johansson, 1997b) to 11%-17% (Dreyfus and Viscusi, 1995). Using conjoint choice questions to evaluate preferences of Italians for income and future mortality risk reductions delivered by contaminated site remediation, Alberini et al. (2007) find that respondents' implicit discount rate is 7%.

Regarding familial altruism, only the weight α_k that takes into account children under 18 is significant in both models with values .12 in **Model I** (p = 0.033) and .1105 in **Model II** (p = .02). The VOLY of one child under 18 is therefore approximately 11% that of the respondent whatever the model considered. This indicates that respondents only consider the benefits for themselves and, to a lesser degree, for children under 18 when doing the valuation exercise. Additional adult household members do not make a difference in respondents' values (α_a is negative but not significant in both models, p = .85 and p = .15 respectively). This is an interesting result since, contrary to other stated preferences studies which find altruism to be significant (see for instance Dickie and Messman 2004), we did not ask respondents to value explicitly the benefits to other household members. Rather, implicit preferences for relatives are derived from the structural model.

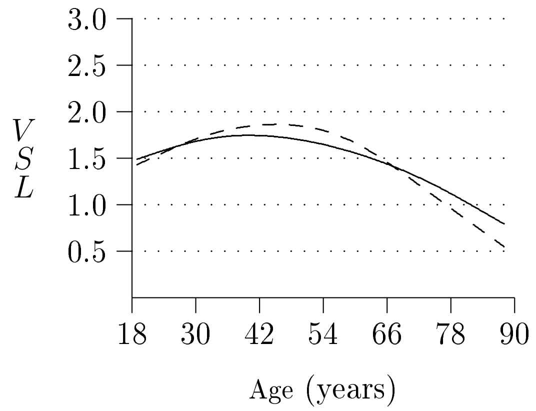
Based on the estimated parameters, we compute mean and median VOLY for both models. In Model I, the constant parameter translates directly into a mean (and median) VOLY at €160,700. In Model II, the mean VOLY is € 150,498 (median €147,994). Using Model II, it is also possible to compute a mean VOLY in perfect health. This is done by computing the mean VOLY for our sample but with *Health75* set to perfect health (*i.e.* 10) for all respondents,[15] *i.e.* as if all respondents were expecting perfect health when length-of-life gains occur. Mean VOLY in perfect health is € 206,808. This is in line with monetary valuations of a QALY based on WTP found in the literature: Johannesson and Meltzer (1998) suggest an estimate between \$ 190,000 and \$ 450,000 and, in a meta-analysis, Hirth et al. (2000) provide a median estimate of \$ 265,000.

We now consider the relationship between age and individual VPF for both models. We do so by first estimating the individual VPF for each respondent according to equation (12) using his/her estimated VOLY (the constant parameter in **Model I** or $\widehat{VOLY}_i$ in **Model II**), and the estimated discount rate $\hat{\delta}$. We then compute non-parametric spline regressions of the relationship between estimated VPF and age. In order to check the validity of our findings, we also compute spline estimations for the original data, *i.e.* $(d\mu_i)^{-1}WTP_i$, with age. Note that in the original data, WTP_i includes WTP for respondent as well as for other household members. Results are presented in Figures (1.a), (1.b) and (1.c), and indicate that the estimated VPF are positive for the whole age range (18 to 90) whatever the Model and the sample.

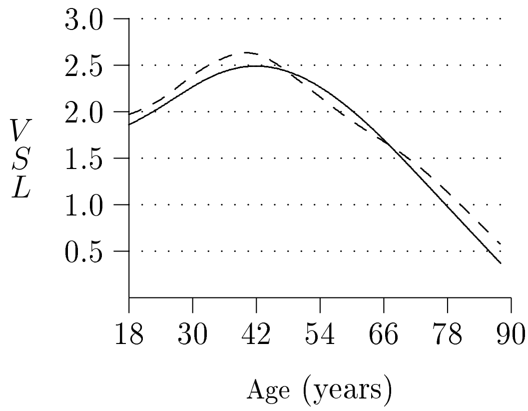
[15] Expected health at 75 years old was elicited using a visual analog scale from 0 to 10.



(a) Model I: whole sample ($N = 907$)



(b) Model II: single respondents only ($N = 175$)



(c) Model II: whole sample ($N = 907$)

Figure 1: Estimated VSL (in € million) by age

Figure (1.a) presents the results for **Model I** as well as the spline regression based on the original data. The VPF based on **Model I** exhibits a monotonic declining trend imposed by the structural model (in **Model I**, the VOLY is constant for all respondents): VPF are lower for advanced ages (like in Johannesson et Johansson, 1996; Krupnick et al., 2002; or Alberini et al., 2004). It does not, however, fit well with the spline regression based on the original data which exhibits a non-monotonic trend between VPF and age: first increasing with a maximum at age 40, and decreasing thereafter.

Figure (1.b) and (1.c) present the results derived from parameter estimates of **Model II**. In Figure (1.b), the spline estimation is performed for single respondents only, while in Figure (1.c) we present the estimations on the whole sample. Both Figures show that, when heterogeneity across respondents is taken into account, our econometric model performs relatively well and exhibits an inverse U-shaped relationship between VPF and age like that found in previous studies – with a maximum at € 1.7 million for single respondents and € 2.5 million for non-single respondents. These results are in line with the literature, both in empirical models on lifetime utility maximization (see Shepard and Zeckhauser, 1984) and in empirical estimates of VPF (Regens 1991, Chilton et al., 1998, Johannesson et Johansson, 1996, 1997, Krupnick et al., 2000, Vassanadumrongdee and Matsuoka 2005 or Krupnick, 2007). The mean VPF for the whole sample is **€2.15** million. For single respondents, the curves have a similar shape with a slightly higher VPF for respondents around 45 when computed using the parameter estimates from the econometric model. When the whole sample is considered, both curves have the same shape, although the VPF based on the econometric model is slightly lower for younger respondents (under 42). This is because in the original data we do not take into account preferences for children under 18 (which are more likely in the household for respondents under 45) and other adults of the household, which are taken into account in the econometric model.

Our results can be contrasted with existing CV surveys specific to air pollution. Working on the same French data, the approach of Chanel et al. (2004) implicitly considers that the respondent exhibits pure altruism and hence attributes a weight of one to every member of his/her household. As a consequence, the average VPF value obtained (about €0.8 million) is lower than that one obtained in this study, as the assumption of equal weight is not supported by the data. As shown in Table 1, the parameters estimated for familial altruism (α_a and α_k) clearly differ from 1. In a scenario eliciting health risks associated with air pollution, Chilton et al. (2004) obtained an average VOLY of €45,000, with a decreasing trend with age, in a sample of UK residents. Vassanadumrongdee and Matsuoka (2005) found a VPF that ranges from €0.74 to 1.32 million when measuring Bangkok residents' WTP to reduce mortality risk arising from air pollution.[16].

Alberini and Chiabai (2006) estimated the WTP of an average 40-year old Italian male to reduce his risk of dying for cardiovascular and respiratory causes. The corresponding VPF is about €2 million and "can be used to estimate the benefits of environmental policies that reduce air pollution" (p. 11). Finally, NewExt (2004) present to 40- to 75-year- old respondents a hypothetical scenario dealing with a mortality risk of the same magnitude as that of air pollution, without any mention of

[16]Their hypothetical scenario specifies that the risk reduction is obtained by a medical health check-up only and is thus not fully contextual

air pollution itself. They found a VOLY of €52,000 (median) and €118,000 (mean) when pooling the CV data of three European countries (France, Italy and UK).

6 Conclusion

In this paper, we propose monetary values for risk of death associated with air pollution. We do so by implementing a contingent valuation survey which involves moving the whole household, with a choice between two cities, one less polluted than the other but with a higher cost of living. We then ask respondents how much they are willing to pay to move to the less polluted city. Because the scenario involves moving the whole household, we need to take into account potential altruism towards other household members. We therefore propose a theoretical framework aimed at defining a VPF that disentangles monetary values associated with the risk of death of the respondent him/herself and monetary values associated with other household members' risk of death.

Our results are two-fold. First, the theoretical model defines an econometric functional form that reveals the (now classic) inverse U-shaped relationship between VPF and age in the specific context of air pollution. The VPF is shown not only to decrease with age (as in Johannesson et Johansson, 1996; Krupnick et al., 2002, Alberini et al., 2004), but to increase up to age 42 and then decrease, with a positive value for the whole age range considered, *i.e.* from 18-year-old to 90-year-old (found for instance in Regens 1991 or Chilton et al., 1998). Johansson (2002) argues that the relationship between age and VPF is model-dependent, i.e. it depends on theoretical assumptions. In that sense, our theoretical framework is not an exception. However, relaxing the assumption of equal VOLY across respondents in **Model II** provides enough flexibility to nicely match the relationship between age and VPF found in the original data. Second, we assess a VOLY associated with air pollution risk of death of €150,000, which translates into a VPF with a maximum of €2.5 million at age 42 with a mean of €2.15 million. This is in line with the monetary values already available in the literature.

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A Computation of $d\mu$

This appendix presents how the $d\mu$ were computed, and clarifies the following wording used in the scenario "if you take 100 persons living in LESSPOL, ONE will die before 80 because of his/her bad health due to air pollution". The superscript n is omitted, and the following is valid for any individual of age t.

A Gompertz function is generally chosen to approximate the death probability of an individual at age j: $\mu(j) = ce^{bj}$(cf Leksell et Rabl, 2001; or Johannesson et al., 1997). Estimation on French mortality data (Insee, 1999) leads to the following (see Figure 1):

$$\mu(j) = ce^{bj} = 0.00007345e^{0.081245106\times j} \quad R^2 = 0.9959 \tag{17}$$

The corresponding conditional survivor function, i.e. the probability of being alive at age t conditional on having survived until age$j$, is:

$$S_{t,j} = e^{\int_j^t \mu(s)ds =} e^{\int_j^t ce^{bs}ds} \tag{18}$$

The concept of Relative Risk is used to represent the effect of long-term air pollution exposure on mortality. It supposes that the death rate $\mu(j)$ is affected proportionally by air pollution exposure:

$$\mu(j) = RR\mu_0(j) \tag{19}$$

where $\mu_0(j)$ is the death rate that would be observed without air pollution. The change in the death rate $d\mu$ that corresponds to the existence of this relative risk between the median age in the population (35 years in 1999) and the age of 80, is computed by solving the following:

$$e^{-RR^{-1}\int_{35}^{80} ce^{bs}ds} = e^{\int_{35}^{80}(ce^{bs}-d\mu)ds} \tag{20}$$

Hence:

$$d\mu = \frac{\int_{35}^{80} ce^{bs}ds[1 - RR^{-1}]}{45} \tag{21}$$

Particulate Matter of diameter lower than 10 μm (PM10) is used as the pollution indicator. French weighted average exposure is assessed at 23.5 $\mu g/m^3$ (see Filliger et al. 1999), in the range of the two local air pollution measuring networks (Airmaraix for the most urban area, 28 $\mu g/m^3$ and Airfobep for the most rural and industrial part, 21 $\mu g/m^3$). The level of 7.5 $\mu g/m^3$ constitutes the natural level that would be observed in the absence of anthropic emissions.

Künzli et al. (2000), estimated the RR of mortality due to air pollution exposure at 1.043 for a 10 $\mu g/m^3$ PM10 variation, i.e. $RR = 1 + (0.043\Delta c)$ for a Δc variation. The scale of reductions used in the survey is $\Delta c = 23.5 - 7.5 = 16$ $\mu g/m^3$ for complete elimination, $\Delta c = 8$ $\mu g/m^3$ for a 50% reduction, and $\Delta c = 4$ $\mu g/m^3$ for a 25% reduction. Since we consider a reduction for the succeeding-year and an age-independent effect of air pollution exposure on death rate, the corresponding changes in the mortality rates are, by (21), $d\mu^{16}$=0.0008378, $d\mu^{8}$=0.0004328, and $d\mu^{4}$=0.0002200.

Note that the right-hand side in equation (20) allows us to compute the number of deaths attributable to air pollution as presented in the scenario. The conditional survivor probability $S_{80,35}$ is equal to 0.5568 before reduction, to 0.5677 for a 50% reduction, and to 0.5781 for complete elimination. Converted to a "per 100 persons" base, this leads to 1.09 person (rounded to one) for a 50% reduction and 2.13 persons (rounded to two) for complete elimination.

B Hypothetical scenario

A translation of the scenario presented to respondents and relevant to the study is reproduced below.

« *You are going to be the central character in our scenario. You will have to take the best decision for yourself and your household.*

Let's imagine that you and your household have to move. You can choose between two cities which are exactly equivalent in terms of inhabitants, working conditions, schools, climate, public services, cultural life, transport, housing, surroundings, etc. There is only one difference between them: the level of atmospheric pollution. The first city - let's call it POL - is as polluted as Marseilles. And the second city - let's call it LESSPOL - is half as polluted as Marseilles.

The problem is that the cost of living is higher in LESSPOL (the less polluted city): housing, local taxes, public transport, etc. are more expensive. This means that if you choose to move to LESSPOL, you will have to pay more to have the same standard of living as in POL.

Actually, *few people realize the impact of air pollution. There are three different types of effects: pure polluting effects, irritant effects, and fatal effects.*

The pure polluting effects cause a cloud of brown dust. They make buildings dirty, so that they need to be more frequently cleaned and smell bad.

The irritant effects cause health problems: irritated eyes, headaches, sore throats, coughing fits, flu symptoms and even hospitalizations for respiratory and heart conditions.

The fatal effects shorten life. If you are exposed for several years to a high level of air pollution, you will be less healthy, and you will die earlier. If you take 100 people living in LESSPOL, ONE will die before 80 because of his/her poor health related to low air quality. This person will have lost around 10 years of life. If these 100 people live in POL, TWO of them will die. We can hence say that 1 person per 100 can live 10 years more by living in LESSPOL rather than in POL.

We would like to know how much you would be willing to pay per month for you and your household to move to LESSPOL (the less polluted city) rather than to POL *(the town as polluted as Marseilles). Do not forget that this money will be drawn from your household's budget! You will therefore have less money at the end of the month. »*

C Sample characteristics

Variable	Description	Mean (sd)
Sex	Gender (Male=1)	.445
		(.497)
NPers	Number of persons	2.776
	in the household	(1.441)
NMinors	Number of minors	0.562
	in the household	(0.953)
Age	Age of the respondent	38.134
	(years)	(17.52)
HHincome	Monthly household	1616.87
	income (€)	(1259.21)
Edu1	Primary-level	.407
	education (=1)	(.491)
Edu2	Senior high school	.215
	education level (=1)	(.411)
Edu3	University-level	.378
	education (=1)	(.485)
BadQuali	Respondent says that the air quality where	.165
	they reside is lower than Marseilles (=1)	(.372)
HealthImp	Respondent declares caring	.698
	about his/her health (=1)	(.459)
Hab	Respondent changes habits during	.294
	highly polluted days (=1)	(.456)
FreshAir	Respondent declares going regularly	.626
	in the countryside to breath pure air (=1)	(.484)
Sport	Respondent's level of sport	1.556
	activities from 0 (none) to 3 (regular)	(1.221)
AirPur	Respondent declares possessing	.017
	an air purifier (=1)	(.132)
OrgFood	Respondent declares regular consumption of	.171
	organic food (=1)	(.376)
RCinter	Respondent has been interviewed in	.273
	Regional Council (=1)	(.445)
CurHealth	Self-reported current state of health	6.307
	visual analog scale (from 0 to 10)	(2.11)
Health75	Self-reported expected state of health at	4.220
	age 75, visual analog scale (from 0 to 10)	(2.95)